Prospects for investigation of radiative top quark processes $t\bar{t}\gamma$ at the ATLAS detector

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Why investigating top photon radiation?

1. Determination of the electric charge Q_t of the top quark
   - QED: $|\mathcal{M}_{t\to t\gamma}|^2 \propto {Q_t}^2$ (Standard model (SM): $Q_t = +2e/3$)
   - Model with exotic top quark $\tilde{t}$ with $Q_{\tilde{t}} = -4e/3$ only excluded at 95% CL (Tevatron)
     $\rightarrow$ Look for differences in $t\bar{t}\gamma$ spectra
2. Measurement of the electro-magnetic form factors of the top quark:

$$
\begin{aligned}
-i\Gamma_\mu^{tt\gamma} &= e\gamma_\mu \left(V_{tt}^\gamma(s) + A_{tt}^\gamma(s)\gamma_5 \right) \\
&+ e\sigma_{\mu\nu}\left(q+\bar{q}\right)^\nu \left[i\frac{a_t^\gamma(s)}{2m_t} - \frac{d_t^\gamma(s)}{e}\gamma_5 \right]
\end{aligned}
$$

Factor	Interpretation	SM value
$V_{tt}^\gamma(s)$	electric charge	$-2e/3$
$A_{tt}^\gamma(s)$	axial-vectorial coupling	0
$a_t^\gamma(s)$	anomalous magnetic form factor	0
$d_t^\gamma(s)$	electric dipole form factor	0

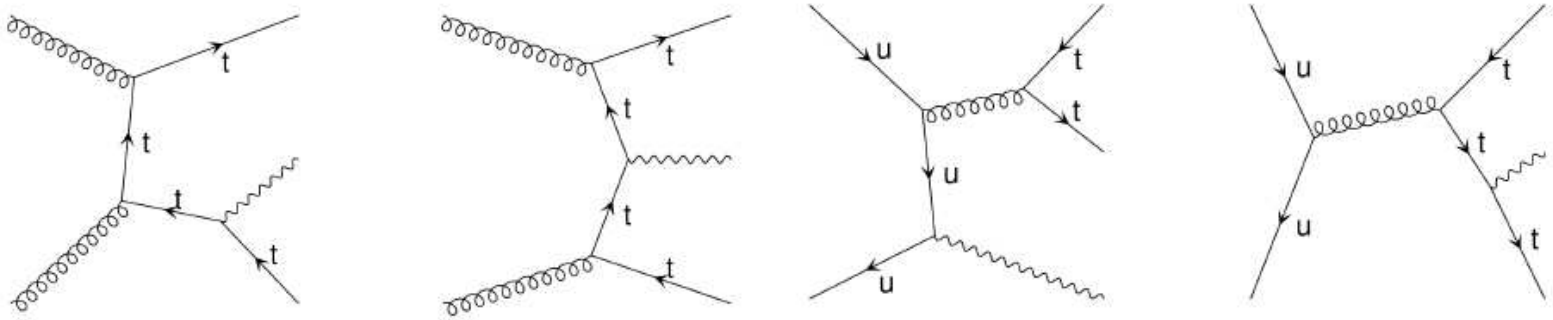
The process $pp \to t\bar{t}\gamma$ (1)

- $pp \to t\bar{t}\gamma \to bW^+\bar{b}W^-\gamma$ can be separated into 2 sub-processes:
  - Radiative top quark production: $pp \to t\bar{t}\gamma$, $t \to Wb$
    $\widehat{=}$ Radiative correction of $t\bar{t}$ *production vertex*
  - Radiative top quark decay: $pp \to t\bar{t}$, $t \to Wb\gamma$
    $\widehat{=}$ Radiative correction of $t(\bar{t})$-*decay vertex*
- Radiative top quark decay: Also γ coupling to b quark or W boson possible
  $\Rightarrow$ **not sensitive to top quark charge!**
  (**ISR**: γ coupling to initial state quarks)

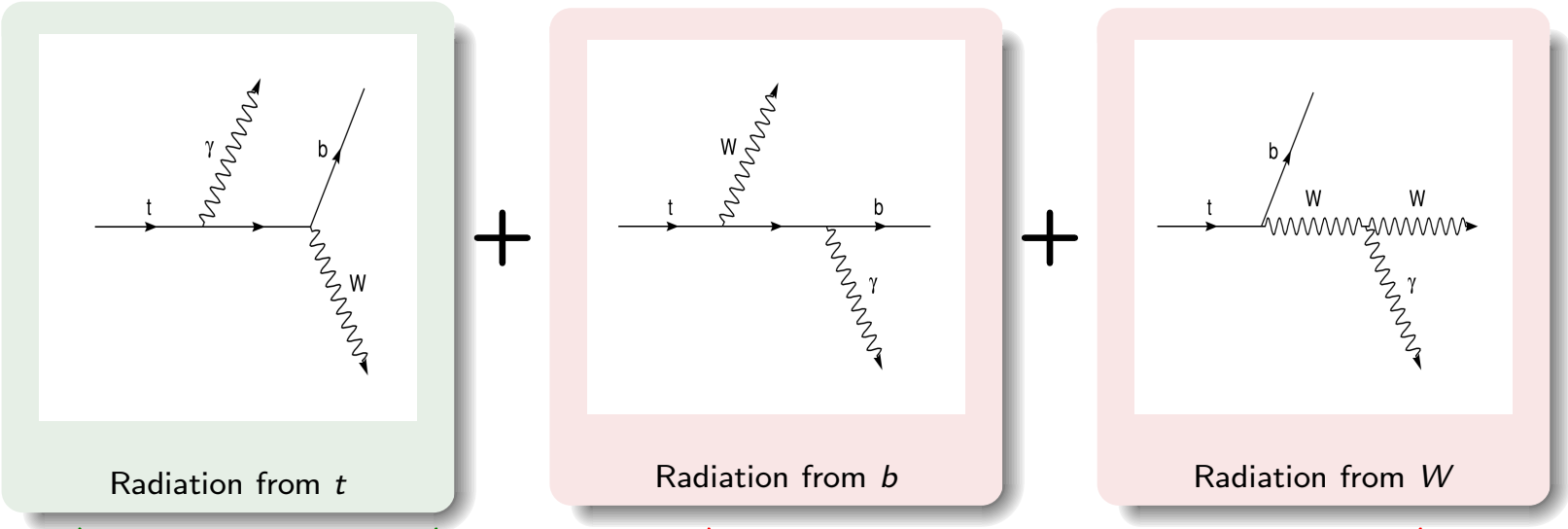
But: $W\gamma/b\gamma/q\gamma$ cannot be disentangled from $t\gamma$ coupling (interference terms)

The process $pp \to t\bar{t}\gamma$ (2)

- Radiative top quark production



- Radiative Top quark decay



MC production of $t\bar{t}\gamma$

- MC generator **WHIZARD** (W. Kilian, T. Ohl, J. Reuter)
  - LO generator with automatic matrix element generation
- 3, 5 and 7 particle final states simulated:
  $pp \to t\bar{t}\gamma$, $pp \to bWbW\gamma$, $pp \to b\ell\nu bq_1\bar{q}_2\gamma$
- $\sqrt{s} = 7\,\text{TeV}$; $p(\gamma) > 10\,\text{GeV}$

Cross sections

σ [fb]	$q_t = \frac{2}{3}e$		$q_t = -\frac{4}{3}e$
$pp \to t\bar{t}\gamma$	931 ± 3	$\xrightarrow{\times 2.29}$	2133 ± 7
$pp \to W^+bW^-\bar{b}\gamma$	2031 ± 4	$\xrightarrow{\times 1.61}$	3266 ± 10
$pp \to b\bar{b}q\bar{q}'e^\pm\nu_e\gamma$	513.4 ± 0.3 [a]	$\xrightarrow{\times 1.19}$	612.6 ± 0.3

[a] **Attention!** 7-particle final state xsecs low due to BR: $\frac{\sigma_{\text{semi-lep}}}{\sigma_{\text{total}}}$

LO vs. NLO calculation

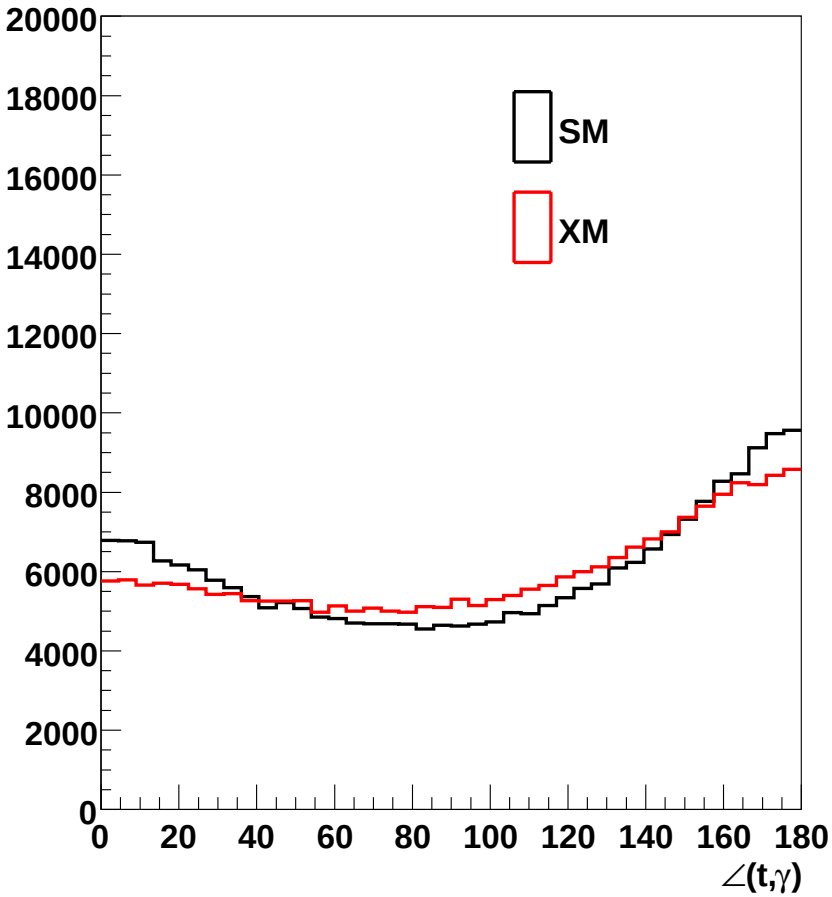
- WHIZARD: Only LO calculation of $t\bar{t}\gamma$ xsec
  $\Rightarrow$ large scale dependency of total xsec!
- Calculation of QCD NLO available $\rightarrow$ K-factors! [arXiv:0907.1324v2 [hep-ph]]
  - K-factor for $t\bar{t}\gamma$ calculated for Tevatron RUN II and LHC @ 14 TeV
  - QCD correction only (no QED/EW NLO calculation!)
  - For LHC @ 14 TeV: $K_{\mathrm{QCD}} = 1.524$ (Tevatron: $K_{\mathrm{QCD}} = 0.977$)
  - Re-calculation for 7(8) TeV possible?
- QED NLO calculation not available yet (?)

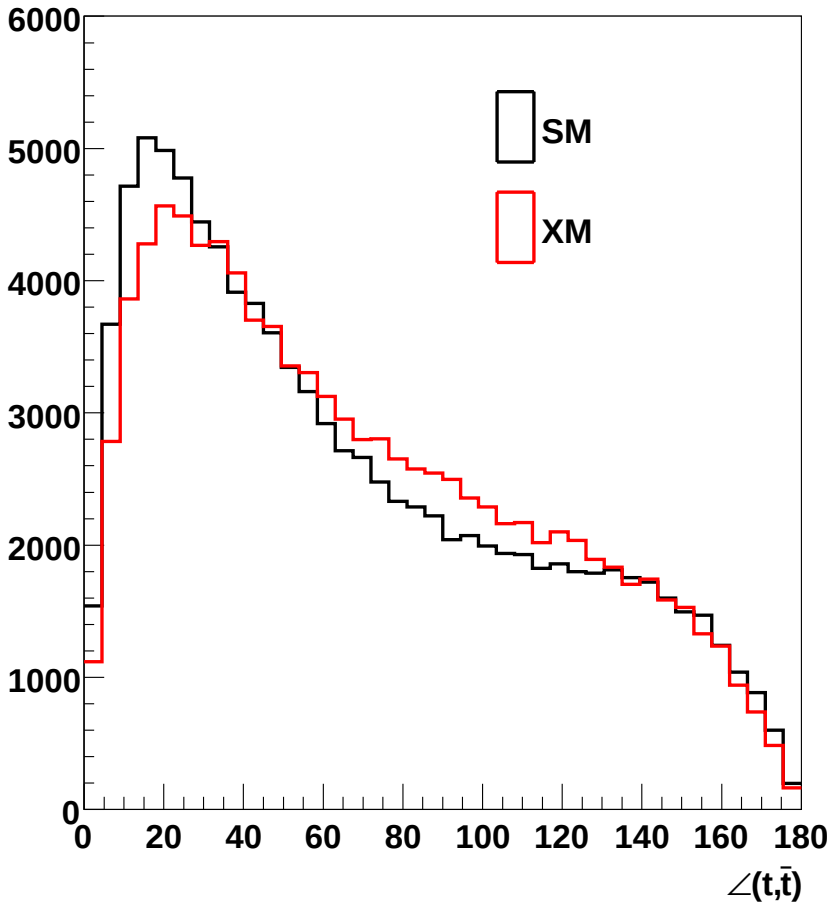
$+2e/3$ vs. $-4e/3$: strategies for model separation (1)

- Total xsec only known up to large scale dependency
- Look for observables most sensitive to $t\gamma$ couplings
- Strategies developed on 4-vector level
  - 7-particle final state official WHIZARD samples ($pp \to b\bar{b}j_1j_2\ell\nu\gamma$) @ 7 TeV
  - 120k events per model (SM/XM)
  - Plots normalized to same number of events
- $\to$ any good transition to reco level possible?

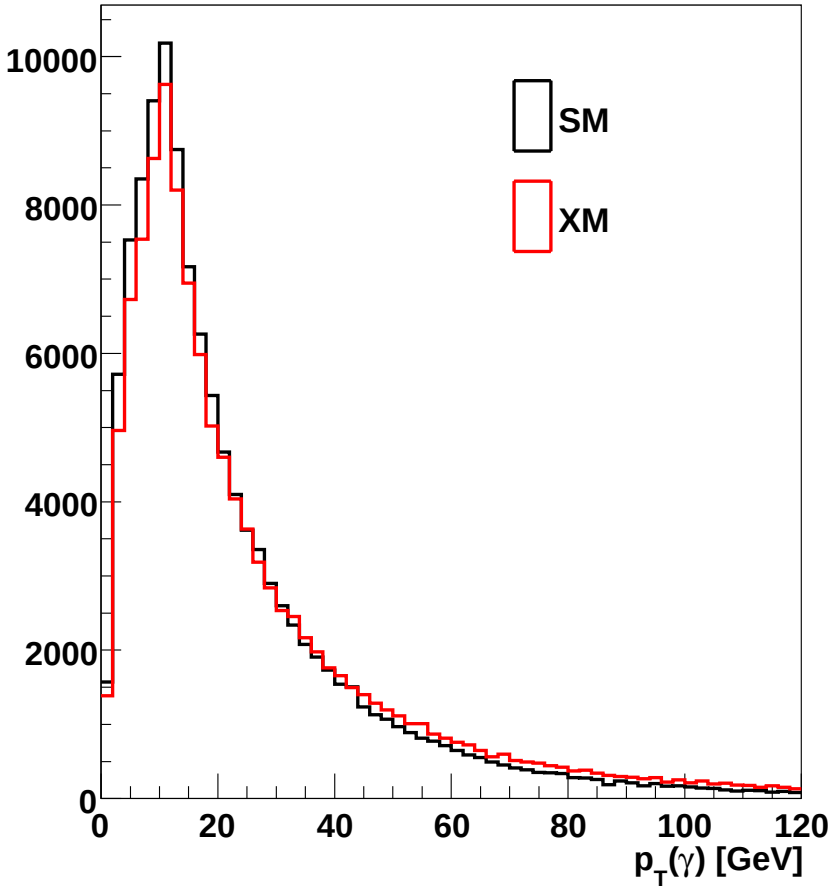
$+2e/3$ vs. $-4e/3$: strategies for model separation (2)

- Compare angle (2D in x-y plane and 3D) between photon and top/anti-top for SM and XM
- Some differences visible $\rightarrow$ will be smeared after reconstruction





$+2e/3$ vs. $-4e/3$: strategies for model separation (3)

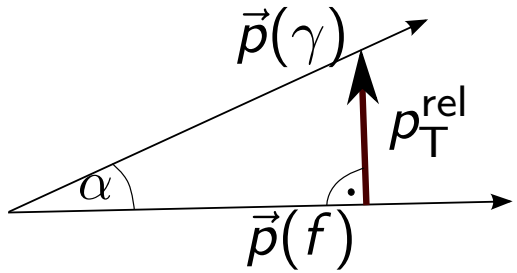


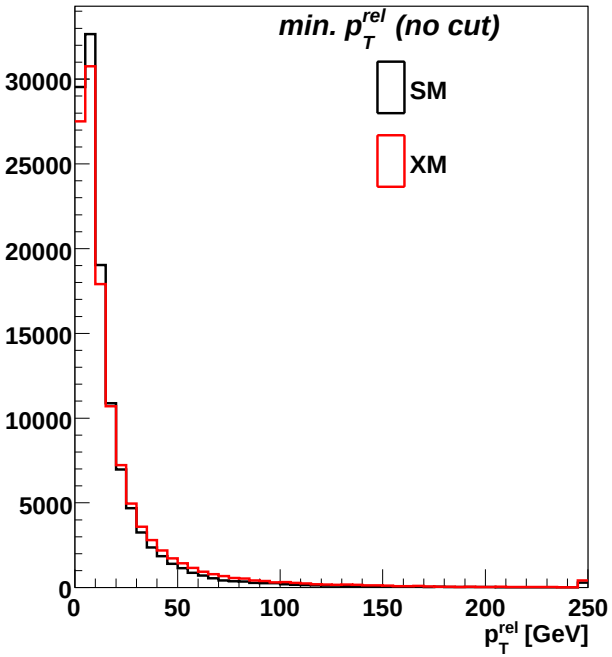
- $p_T(\gamma)$ spectrum for XM slightly harder than for SM

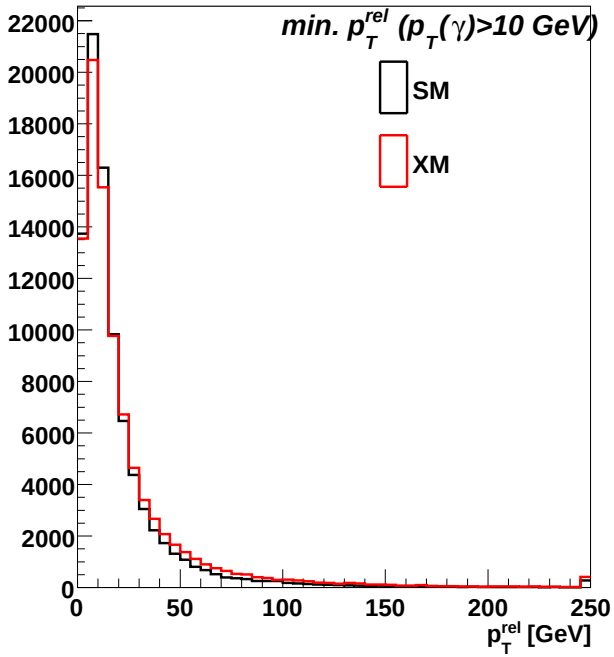
Relative $p_{\mathrm{T}}(f,\gamma)$ (2)

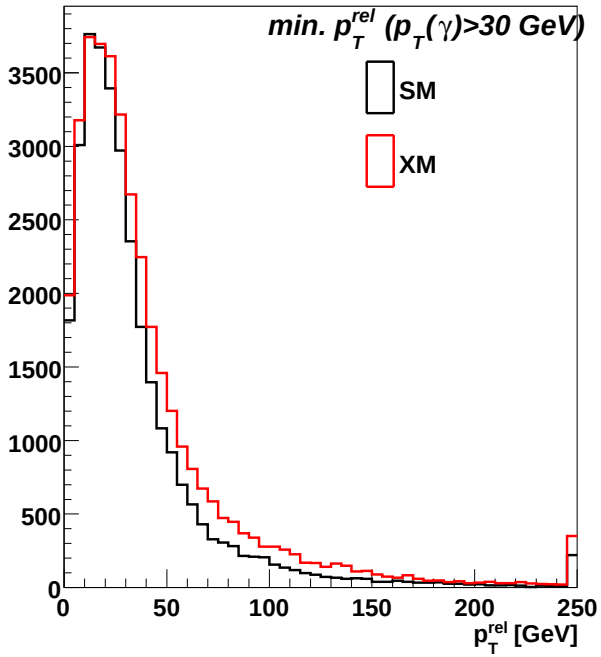
- Consider relative photon p_{T} w.r.t. momentum of some other MC particle f:

$$p_{\mathrm{T}}^{\mathrm{rel}} = \sin(\angle(\gamma, f))\cdot|\vec{p}(\gamma)|$$

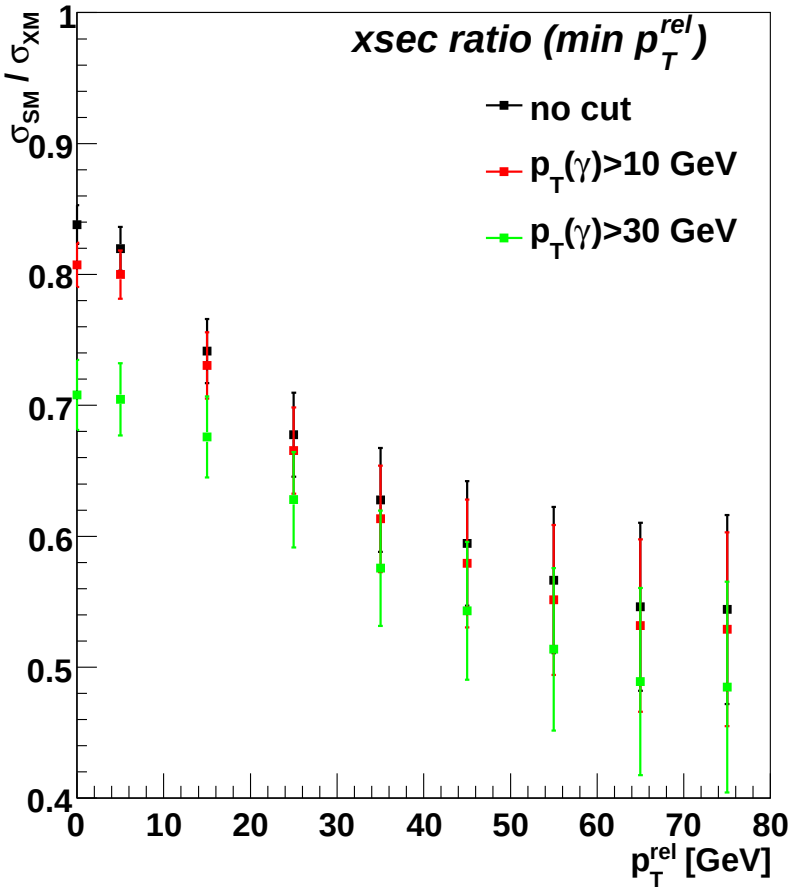


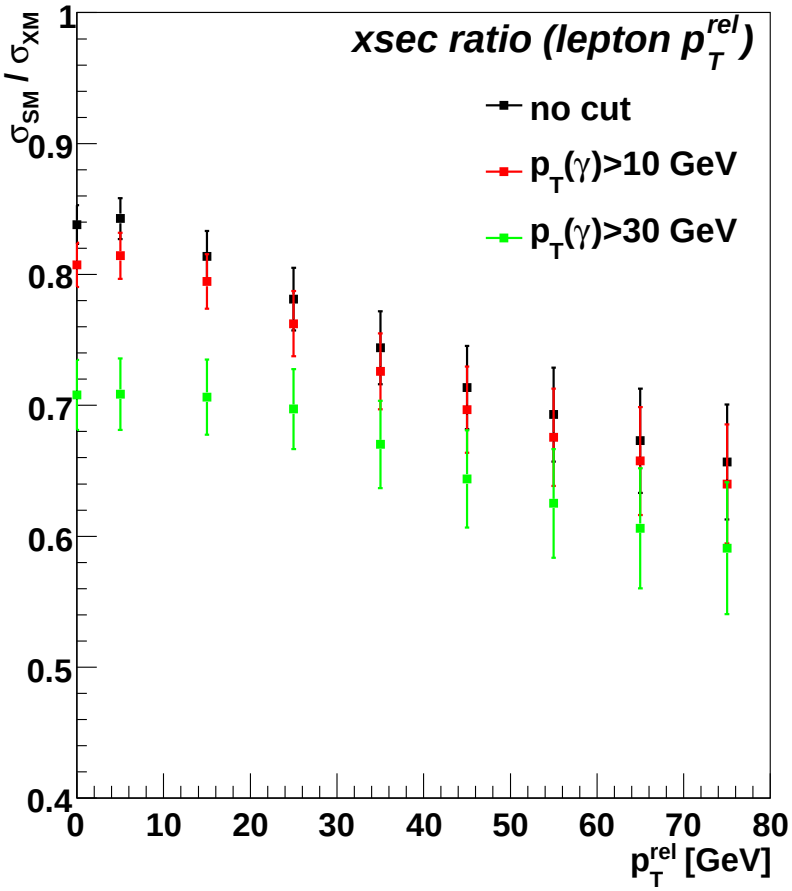






Relative $p_T(f,\gamma)$ (2)





- xsec ratios are calculated from 120k events ($\hat{=}90\,\mathrm{fb}^{-1}$)
- Errors are scaled for $\int L\,dt = 10\,\mathrm{fb}^{-1}$

Factorization of $pp \to t\bar{t}\gamma \to b\bar{b}j_1j_2\ell\nu\gamma$ (1)

- QFT: Only probabilistic interpretation of $t\gamma$ coupling
  $\to$ no unique discrimination possible, **but:**
- WHIZARD 2: Factorization in intermediate sub-processes possible ("narrow width approximation")
- Create two samples ($\sum = 50\,\text{k}$, event number weighted by xsec $\times$ BR):

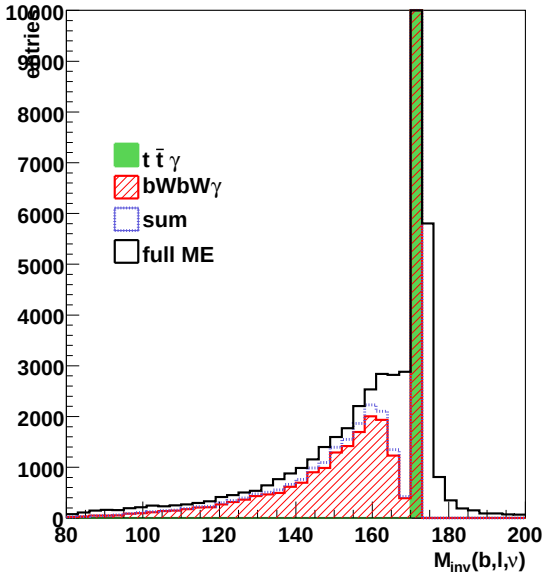
  $pp \to t\bar{t}\gamma \Rightarrow t \to b\ell\nu\ (t \to bq\bar{q}')$

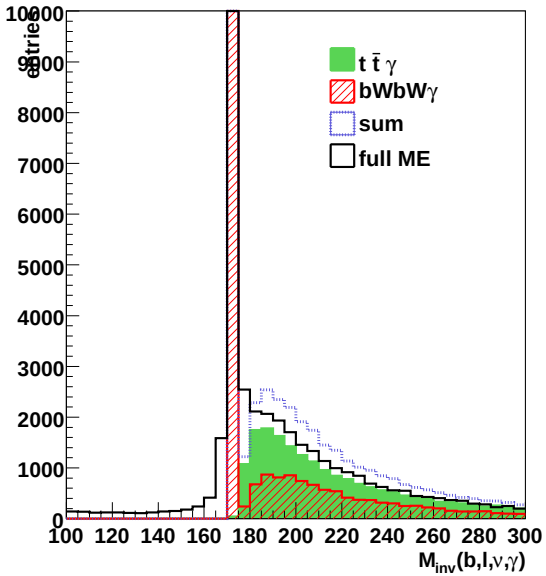
  $pp \to t\bar{t} \Rightarrow t \to b\ell\nu\gamma\ (t \to bq\bar{q}'\gamma)$
- Compare with full ME calculation
  ($pp \to bq\bar{q}'\bar{b}\ell\bar{\nu}\gamma$) (also 50k events)

Cross sections $\times$ BR ($\sqrt{s} = 7\,\text{TeV}$)

$\sigma_{\text{fact.}} \times \text{BR}$	$642,7\,\text{fb}$
$\sigma_{\text{full ME}} \times \text{BR}$	$506,2\,\text{fb}$

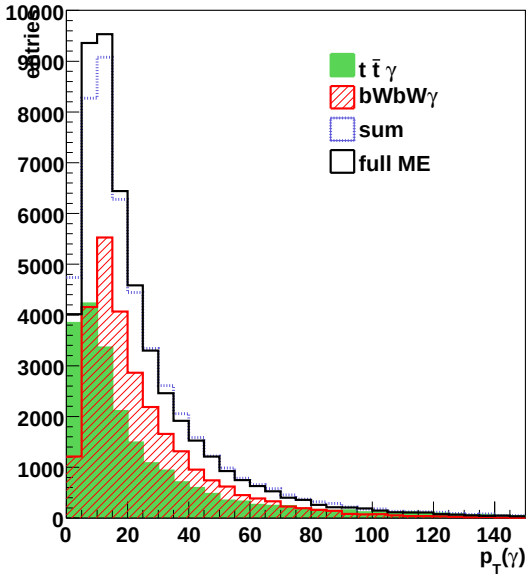
Factorization of $pp \to t\bar{t}\gamma \to b\bar{b}j_1j_2\ell\nu\gamma$ (2)

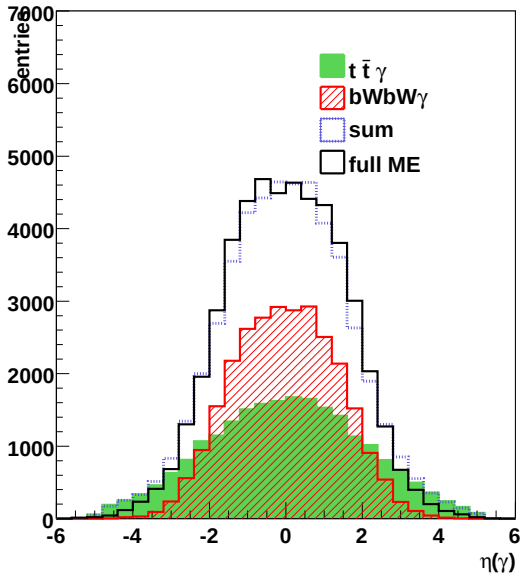




- Look at reconstructed top mass
  - Upper plot: M_{top} reconstructed without photon
  - Lower plot: M_{top} reconstructed with photon
- Height of top mass peak cut in these views
- Far away from top mass peak: Good agreement between full ME calc. and factorization
- Good discriminant! (Disadvantage: exact top mass reconstruction required!)

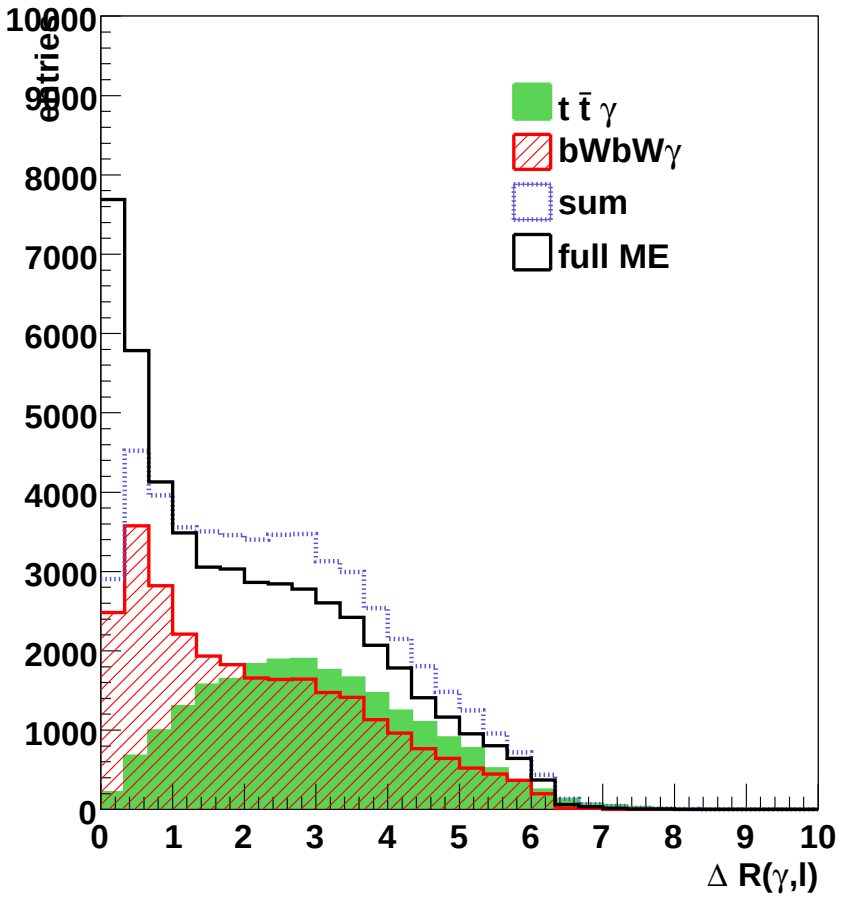
Factorization of $pp \to t\bar{t}\gamma \to b\bar{b}j_1j_2\ell\nu\gamma$ (3)





- Upper plot: signal photon p_T spectrum ($t\gamma$ couplings) softer than background $\to$ not good
- Lower plot: η spectrum: excess for $\eta \gtrapprox 2.0 \to$ difficult to cut for such η range
- p_T and η not good discriminating variables

Factorization of $pp \to t\bar{t}\gamma \to b\bar{b}j_1j_2\ell\nu\gamma$ (4)



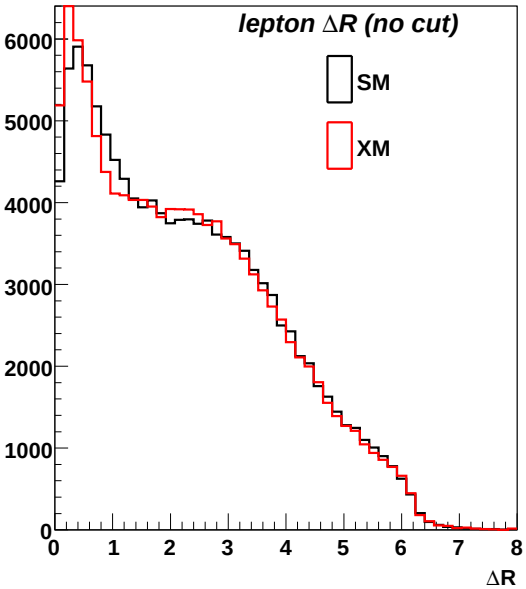
- ΔR between photon and lepton
- In principle: Good separation potential
  $\to$ leptons+photon can be reconstructed with good accuracy!
- But: Poor agreement with full ME!
  $\Rightarrow$ How much can we trust this approximation?

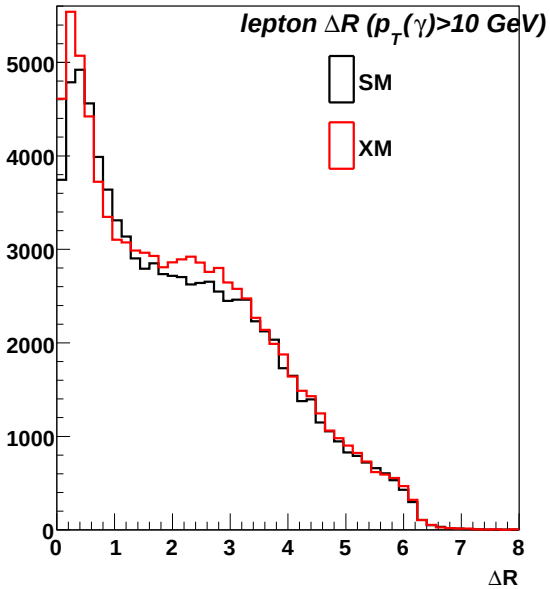
Conclusions/Outlook

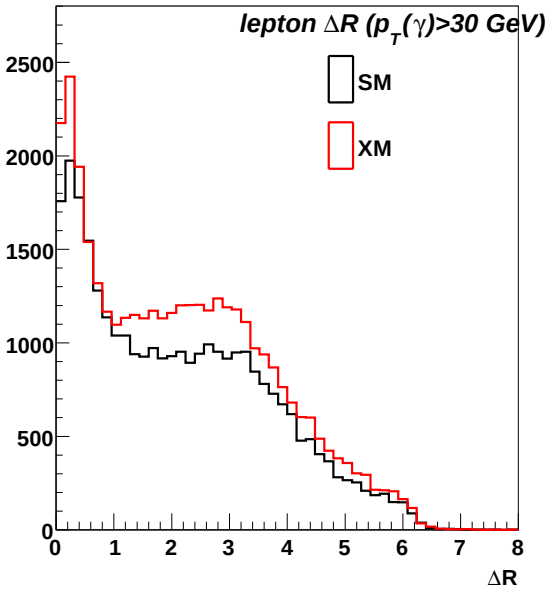
- Investigation of radiative top quark processes $pp \to t\bar{t}\gamma$ important for
  1. Determination of the electric charge of the top quark (SM $+2e/3$ vs. exotic model with $-4e/3$)
  2. Measurement of the electro-magnetic form factors
- MC generator WHIZARD for generating $t\bar{t}\gamma$ events
  - Improvements on absolute xsec prediction via K-factors from QCD NLO calculation?
- Looking further for improvements of SM/XM separation (angular distributions, relative p_T xsec ratios)
- WHIZARD 2: Factorization of $pp \to t\bar{t}\gamma \to b\bar{b}j_1j_2\ell\nu\gamma$ into sub-processes
  - Optimizing phase space cuts to increase gain of $t\gamma$ couplings
- Until mid of 2011: Begin studies on form factors
- **Further discussion very welcome!**

Backup slides

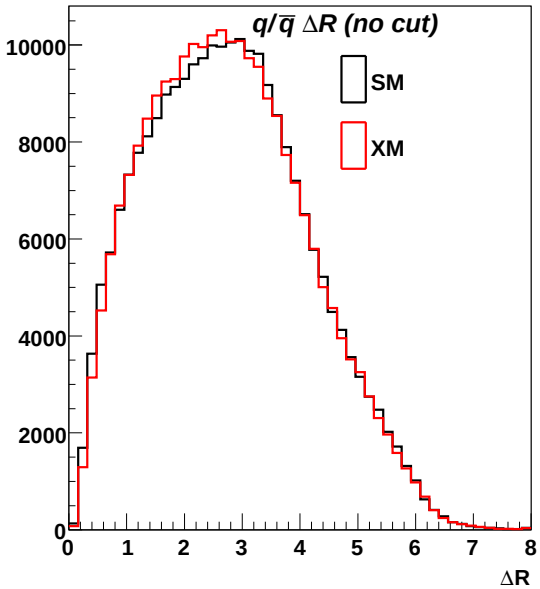
$\Delta R(\ell, \gamma)$

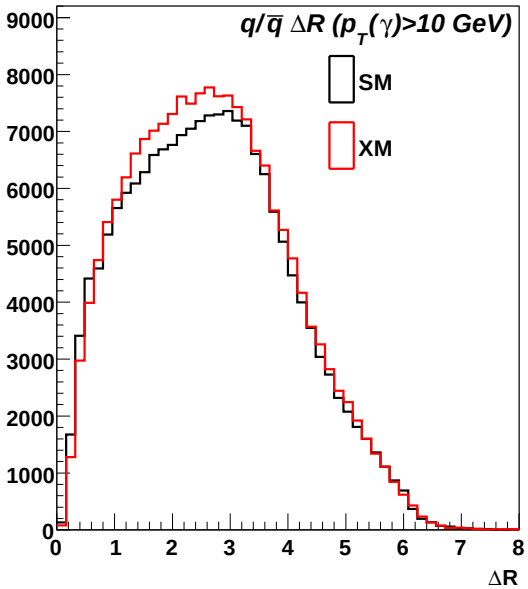


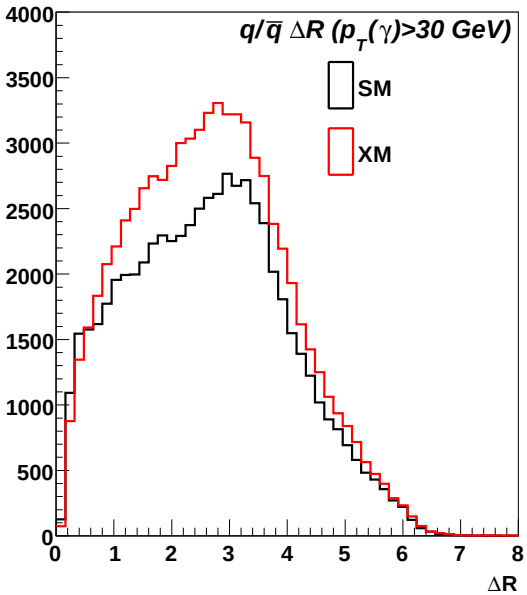




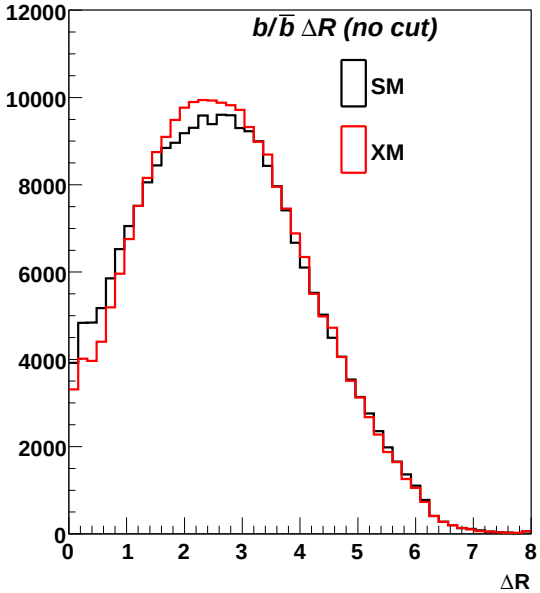
$\Delta R(q/\bar{q}, \gamma)$

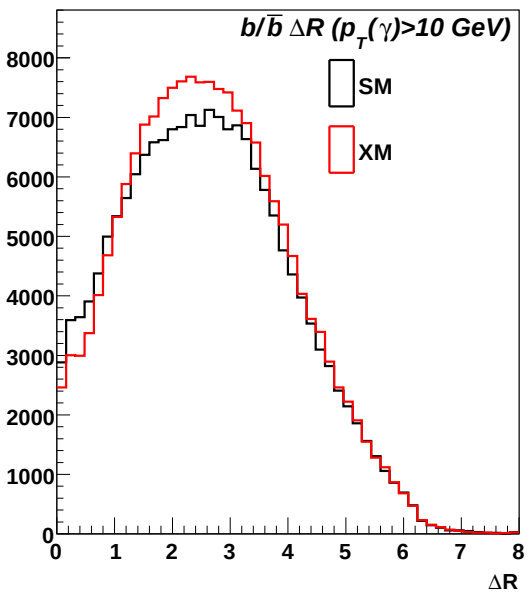


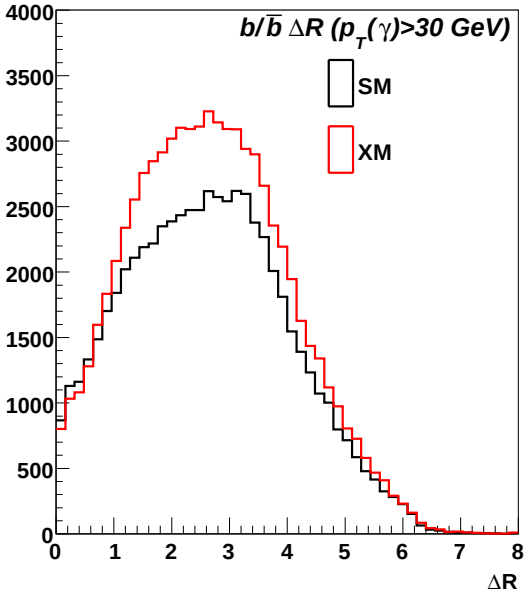




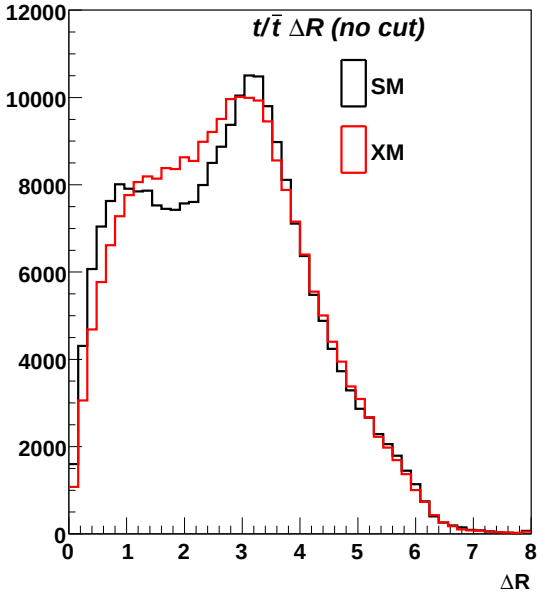
$\Delta R(b/\bar{b}, \gamma)$

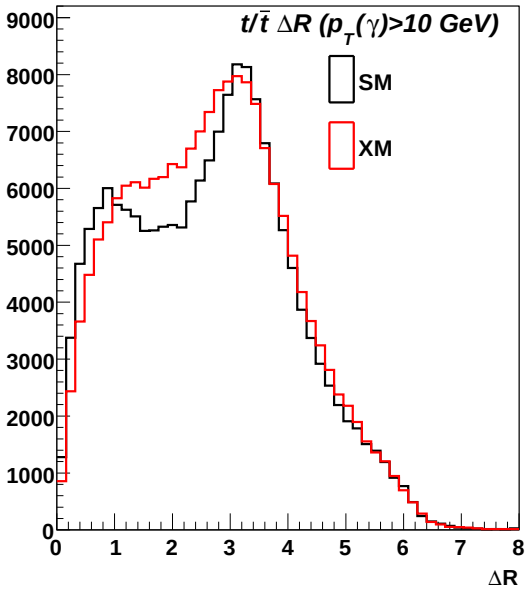


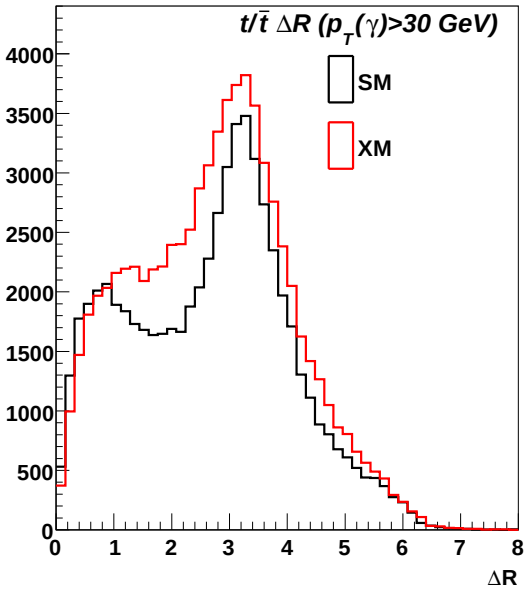




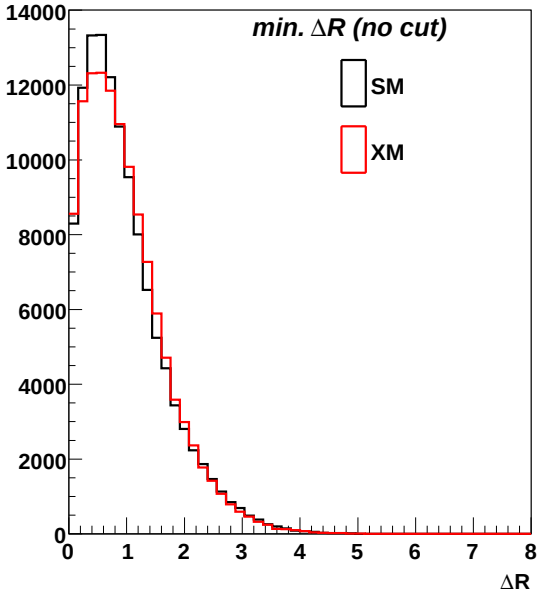
$\Delta R(t/\bar{t}, \gamma)$

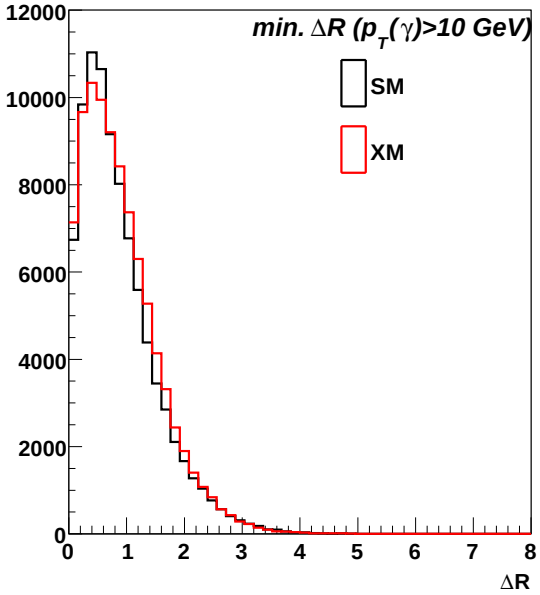


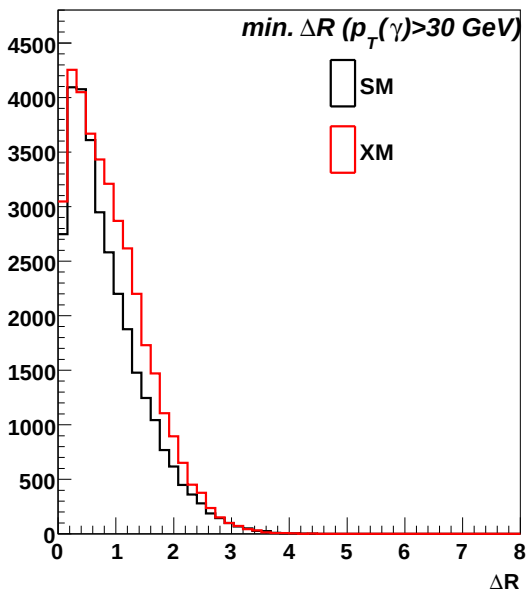




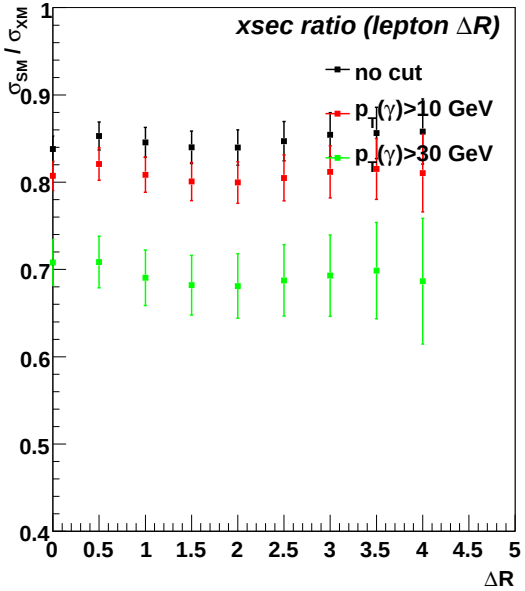
minimum $\Delta R(f, \gamma)$

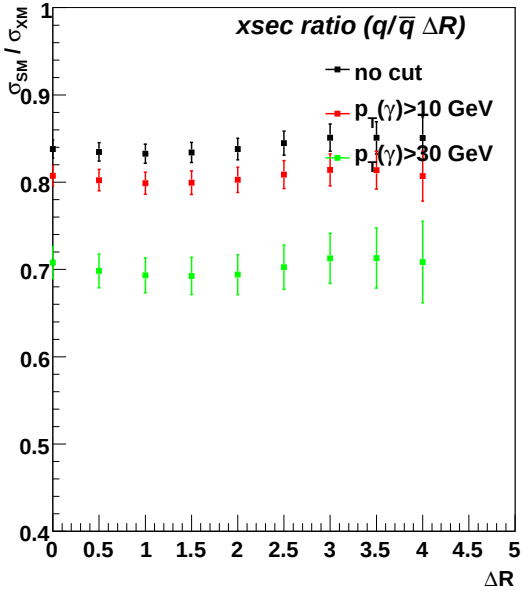


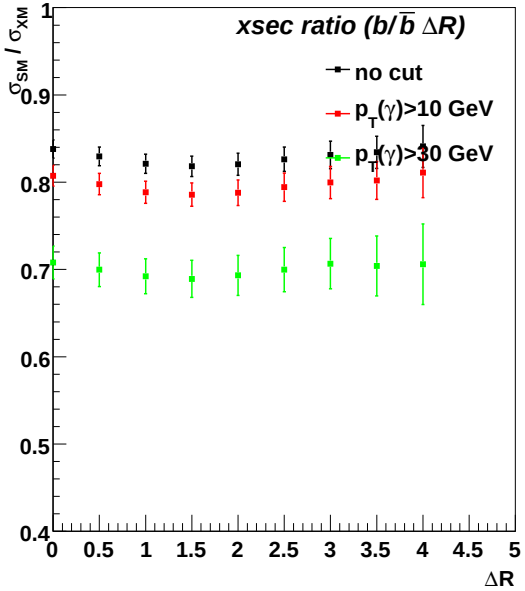


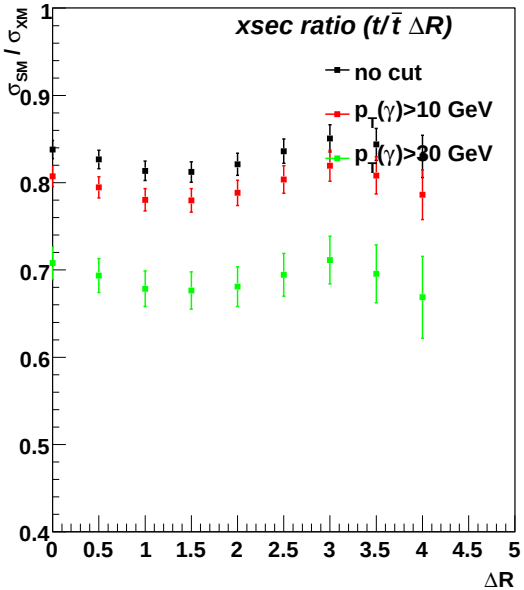


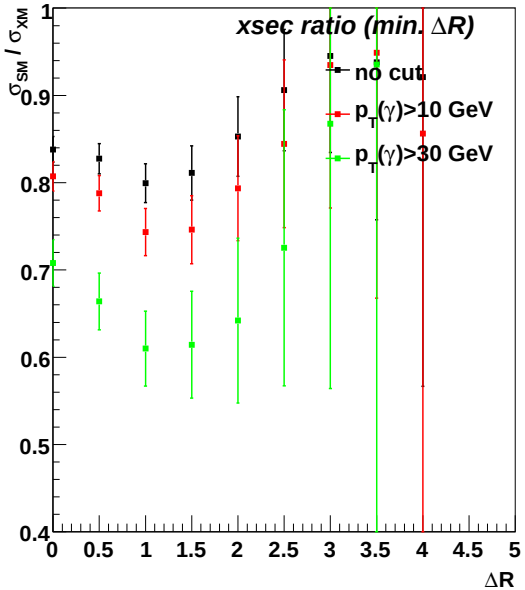
$\Delta R(f, \gamma)$ vs. xsec ratios



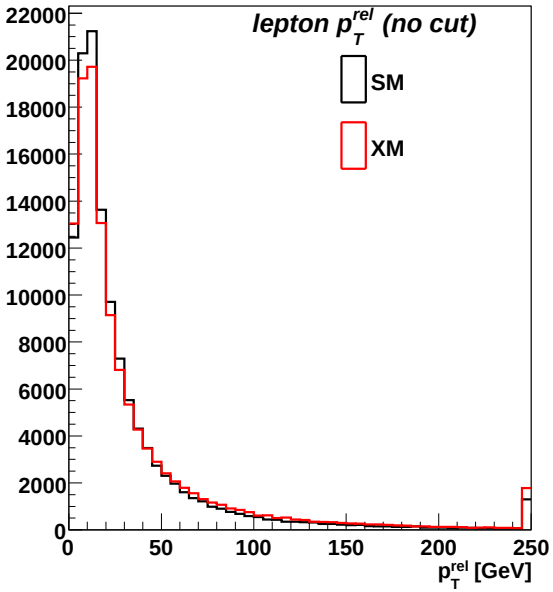


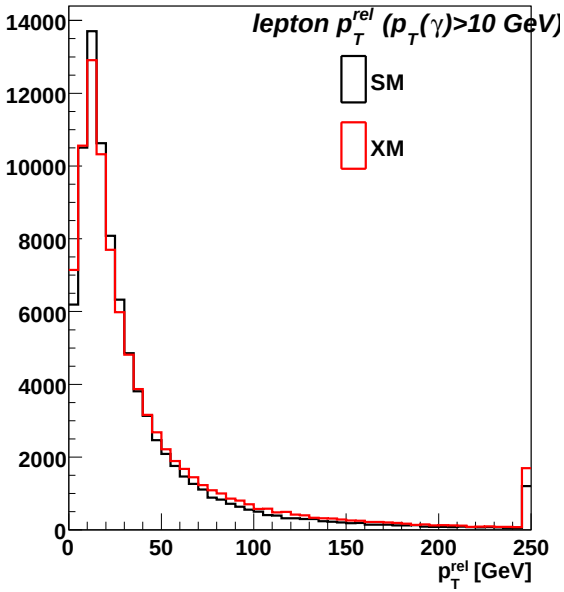


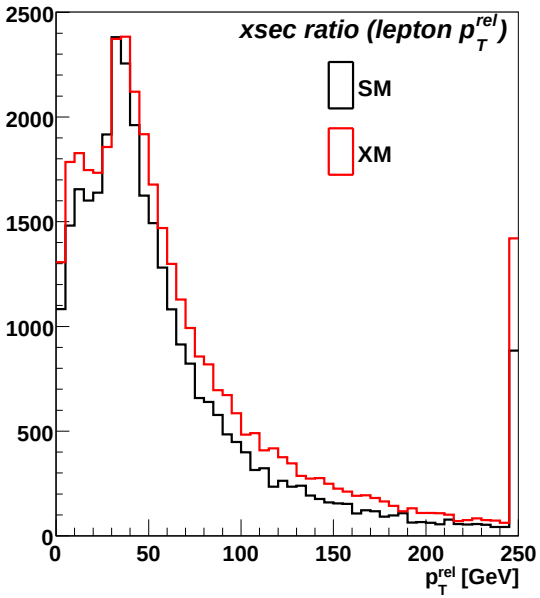




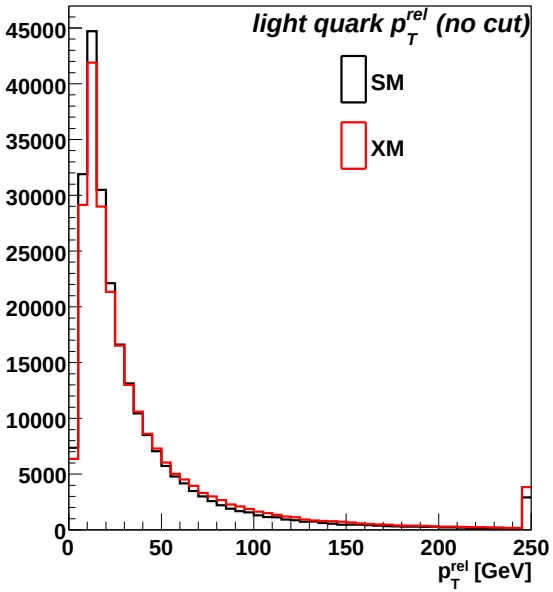
$p_T^{rel}(\ell, \gamma)$

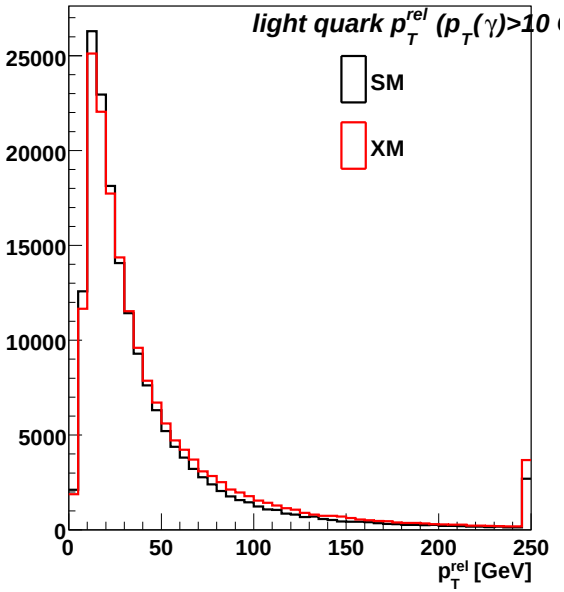


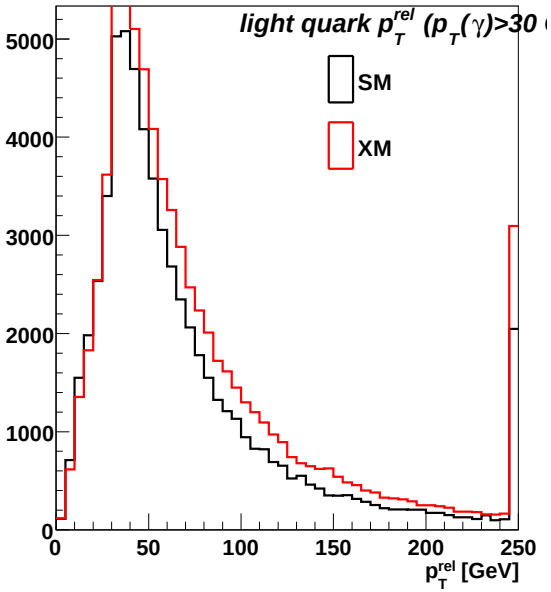




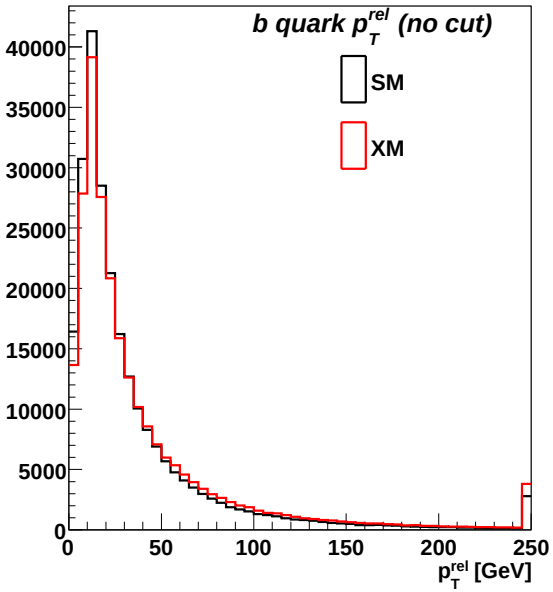
$p_T^{rel}(q/\bar{q}, \gamma)$

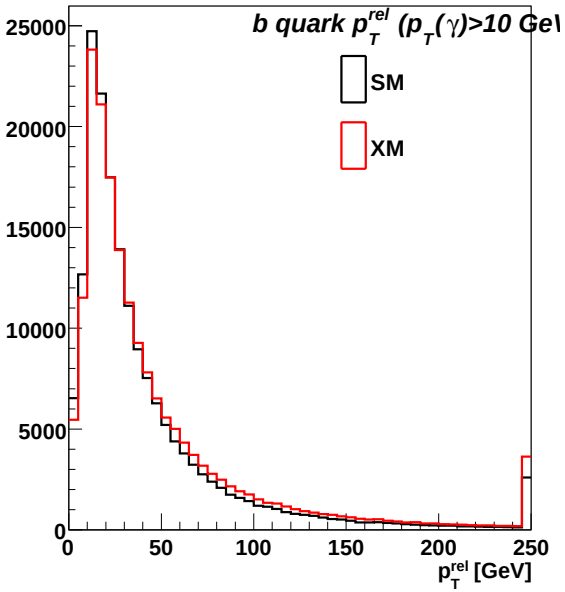


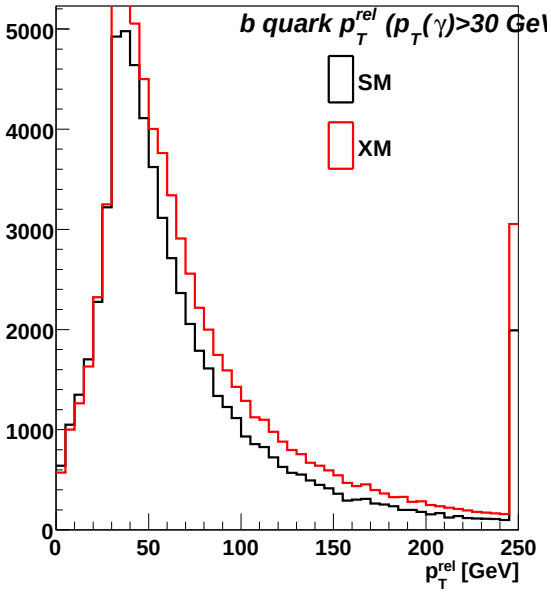




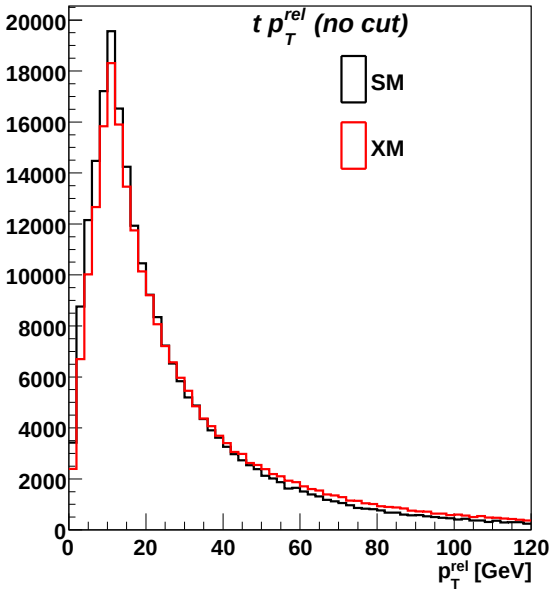
$p_T^{rel}(b/\bar{b}, \gamma)$

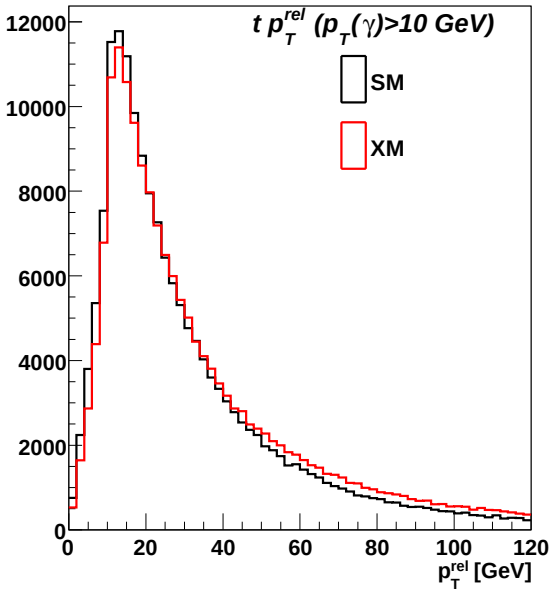


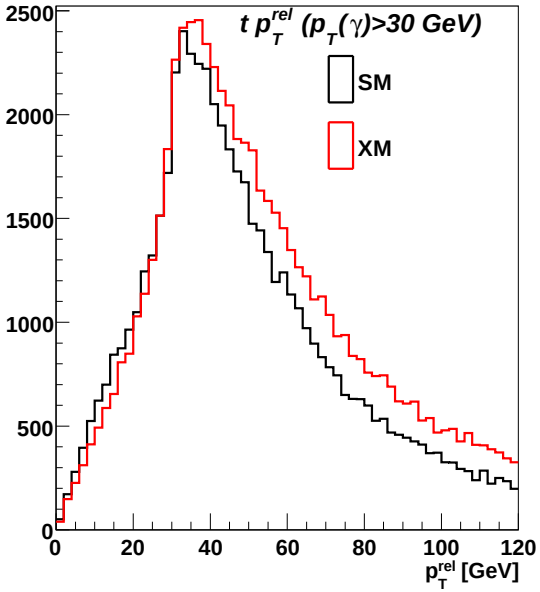




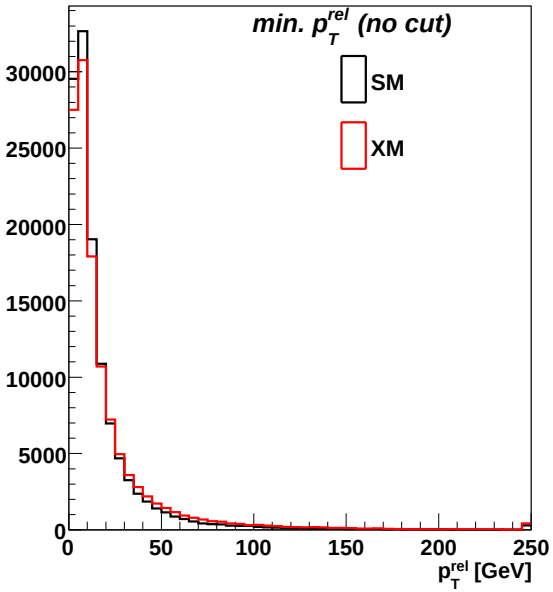
$p_T^{rel}(t/\bar{t},\gamma)$

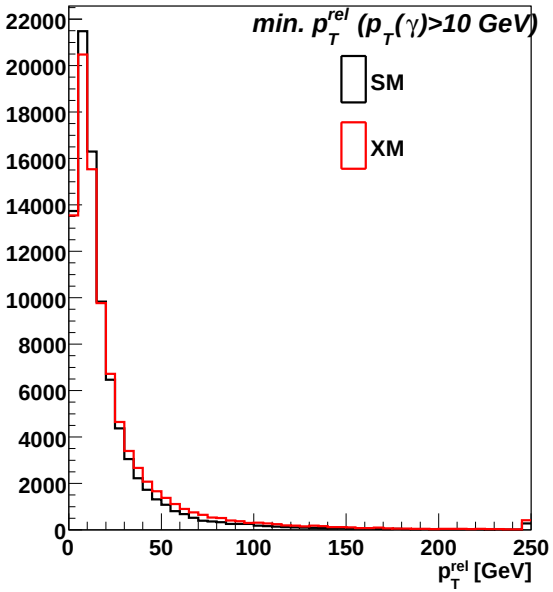


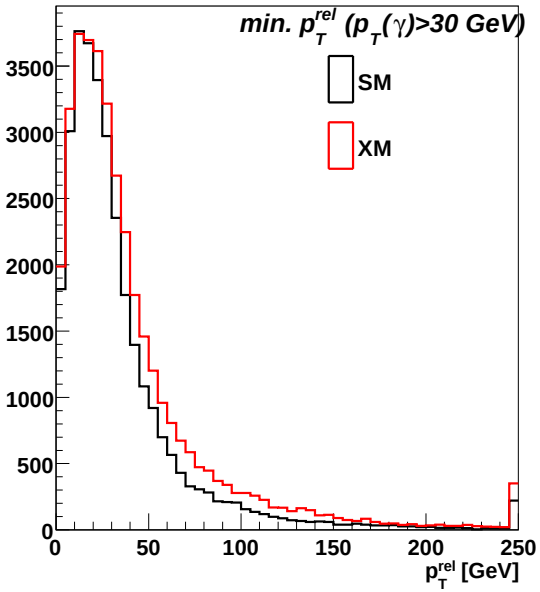




minimum $p_T^{rel}(f,\gamma)$







$p_T^{rel}(f,\gamma)$ vs. xsec ratios